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THE AFRL INTELLIGENT CONTROLS FACILITIES (ICF) GENERIC GAS TURBINE ENGINE MODEL

Delivery Order 0001: Intelligent Controls Facility

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14. ABSTRACT

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The AFRL ICF Generic Gas Turbine Engine Model

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This paper describes the Intelligent Controls Facility (ICF) generic engine model representing the thermodynamics of a 2-spool high bypass turbine engine, with a multi-function controller. This model is used in the Air Force Research Laboratory (AFRL) Propulsion Directorate Intelligent Controls Facility (ICF), where it forms the foundation for interchangeability of simulated and actual controllers, actuators and mechanical and electrical devices in a "Hardware-in-the-Loop" setup. The engine portion of the model incorporates standard thermodynamics so that it can duplicate the station temperatures and pressures for cycles represented by performance programs ("customer decks") and can directly utilize the "Design Point" output of the NASA GRC NPSS program. The generic controller uses integral-proportional controls, with integral gains, proportional gains, delays, holds and transport times.

The authors posit that a real time model (using the dSpace tool set) can produce the interaction expected among engine, controller, sensors and actuators, so that any one of these simulated components can be replaced with the hardware that it represents without impact on the results. A goal is to develop the capability to perform ICF facility for V&V testing of actuators, controllers and life-extending algorithms.

I. Introduction

BACKGROUND

Development effort in the ICF is based on two primary goals. These are 1) To provide original equipment manufacturing (OEM) independent capability for testing, validation, and verification, and 2) To provide non-propriety common model for researchers, especially for small businesses and academia. Additionally, the model can be used to improve the performance of turbine engines and engine control systems over their entire operational lifetime while minimizing constraints placed on the design of other aircraft systems.

The Air Force is responsible for the operation of a wide variety of aircraft turbine engines. These include multiple engine designs produced among multiple vendors, with variations within each of the engine types, and at various stages of their operational lifetimes. A detailed understanding of the operation of each of these engines is required to attack the two primary goals stated above. High fidelity simulation models exist for some engine types but there is currently no standard approach to the development of these models among all vendors. Simulation models are vendor specific making it difficult for decision makers to evaluate and compare engine designs for use in new programs. Models are also proprietary and can not be shared, making coordinated research difficult.

Available simulation models do not account for variations in engines that exist in the fleet nor for changes in operating characteristics over the lifetime of the engine. Existing engine simulation models are typically run repeatedly in batch mode, off-line (non-real time) and require individual data reduction efforts. Steady-state, and transient analysis are typically considered separately. The cost of maintaining simulation models to address these concerns using methods currently employed is prohibitive. There is considerable duplication of effort involved in the development of simulation models and additional training time and expense required to understand and use each new model. In summary, the current framework for the development of high-fidelity turbine engine simulation software, although required for engine control system design, is unnecessarily expensive, time consuming, and is not adequate for advanced control system design, development, evaluation and implementation. A better, more comprehensive framework is needed and is achievable using currently available tools and technology.

The development of a high fidelity, non-linear, generic engine model in a modern software development language at the engine component level encapsulates our knowledge of basic turbine engine operating principles and characteristics. It provides a basic framework for both the development of engine component models and the analysis of component interactions at the system level within the engine. These intentions are in line with Adibhatla, et al [1], Gastineau [2], Parker, et al [3], Numerical Propulsion System Simulation (NPSS) [4], and Yadav, et al [5]. The generic engine model developed at the ICF serves as a starting point for the development of specific high fidelity turbine engine models. Each of these engine models can then be further refined to accurately model design variations applied as the result of engine program development and furthermore, if provided with specific engine operational data from the field, simulation models can be tuned to track the entire history of a specific engine.

In the generic engine model framework, simulation model development is standardized and can be shared among multiple organizations if required. Component modules can be reused and the time and cost required to produce new models significantly reduced. The development cost for engine models is incremental and tradeoff's between model fidelity and development cost can easily be made. These goals are shared with those stated for NPSS [4]. The generic engine model can also capture both steady state and transient behavior of the engine and embed both of these within the same comprehensive model. The use of a modern graphical modeling language for software development also facilitates a direct conversion of the simulation model to a hard real time simulation that can be executed in hardware available within the ICF.

There are several benefits that come from the real time engine simulation capability of the ICF. The analog, digital, and discrete I/O associated with simulation hardware permits the connection, where necessary or desirable, directly to engine components or control systems either for the purpose of verifying engine component models or testing connected hardware and its interaction with other engine components. Analysis of control system designs coupled with real time engine simulation substantially reduces the cost of control system develop and reduces the need for extensive flight testing or the construction of custom testing stations.

The development and validation of advanced turbine engine control systems that seek to optimize engine performance, as posited by Adibhatla [1] and Gastineau [2], depends on 1) knowledge of the engine to be controlled and 2) the availability of measurements characterizing the internal state behavior of the engine as the operating environment and desired engine control actions change. Although it may not be feasible to instrument an engine to the extent necessary to directly measure all internal engine state variables, knowledge of a partial set of state variables together with an accurate engine model may make it feasible to estimate remaining state variables using optimal (Kalman) filtering theory. The availability of a high fidelity engine model facilitates the design of either state observers or optimal filters for state estimation. The ability to test engine model, state estimates, and engine control systems in a real time setting provides a means for formulating, testing and evaluating advanced engine control techniques for optimal engine performance. Control techniques that are proven in a real time control simulation can then be directly implemented in universal FADEC hardware.

The following is a summary of capabilities that can be provided as a service to the AFRL as a result of efforts at the ICF:

1) A tool to understand and improve turbine engine operation and performance.
2) A test bed for the development of advanced engine control system architectures.
3) Modeling of engine performance over its operational lifetime and the ability to predict maintenance requirements.

4) The ability to predict the consequences on engine performance of either specific operational scenarios or modifications to existing engine or control system designs.
5) The use of engine simulation models and control system models as an archive of prior design experience so that this experience can be preserved and reused.
6) The ability to integrate test results from other test facilities into existing or new models, evaluate model performance, and provide recommendations back to component design and/or maintenance groups.

II. Model Development

Model Overview

A generic turbine engine model and an engine control model have been developed in the ICF at Wright Patterson Air Force Base. The ICF has the capability of executing both control system and engine models in real time each in their own general purpose hardware within the test-bed. Work is currently underway to demonstrate the conversion of the generic engine model to fit specific turbine engine designs based on vendor supplied, high fidelity simulation models. Other research in progress at the ICF includes further development of advanced engine control systems, the comparison of real time component simulations and actual engine component test data and the improvement and further development of engine component models.

The engine model was configured and modified for AFRL by Scientific Monitoring, Inc (SMI), as a prototype high bypass, non-augmented, turbofan engine model from its original version by Zane Gastineau [2] . The following requirements were considered:

1) Model shall simulate engine behavior in real time.
2) Model shall operate over the entire flight envelop of the engine.
3) Model shall accurately represent engine steady state behavior, especially at the design point.
4) Model shall credibly represent transient engine behavior.
5) Model shall be easily modified to simulate other turbine engine cycles.
6) Model shall be capable of interfacing with hardware for testing and validation.
7) Model outputs shall simulate engine sensor measurements.
8) Model user inputs shall be environment conditions, PLA and load demands for bleed and power extraction.
9) The generic model must be releasable to researchers by AFRL; there cannot be any restricting intellectual properties or proprietary information in the model.

Based on the above requirements AFRL and SMI decided to develop a model with the following characteristics:

- Physics based (e.g., thermodynamic, inertias, etc.)
- Modular/component based construction.
- Incorporate engine dimensions and component maps for sizing.

The above characteristics are generally used for models that have requirements 1) through 5). The model was developed in Matlab/Simulink (R13) and runs on either a stand-alone PC (single CPU) or hardware-in-the-loop simulation racks with two CPU's. Using Matlab/Simulink in a dSPACE environment enables meeting requirement 1), 6) and 7).

The Simulink model was developed for use in an off-design mode. It is not easy to create new design cycles within this model. It is recommended that the cycle design be carried out using NPSS, and the resultant design parameters be transferred to the data section of this Simulink model.

The engine model is constructed with a component approach for ease of modification and replacement with different engine components. Each component can be instantiated from a software library module developed to represent the functions of that particular type of component. Each module is a functional unit with its own set of inputs and outputs(I/O). Each can function as an independent component. For example the turbine module can be used as a stand-alone turbine component (Figure 1) and it can be used to instantiate high and low pressure turbines in the engine model. The inputs and outputs to the turbine module are shown in Figure 1.

A “lumped” approach is used to create each module. A multiple stage turbine or compressor is simulated as one component. This approach is adopted because turbine and compressor maps are created to represent the performance of the overall component, not in a stage-by-stage fashion. This lumped approach does not violate any of the model requirements (though it may limit the validity of the performance) and is the industry traditional approach.

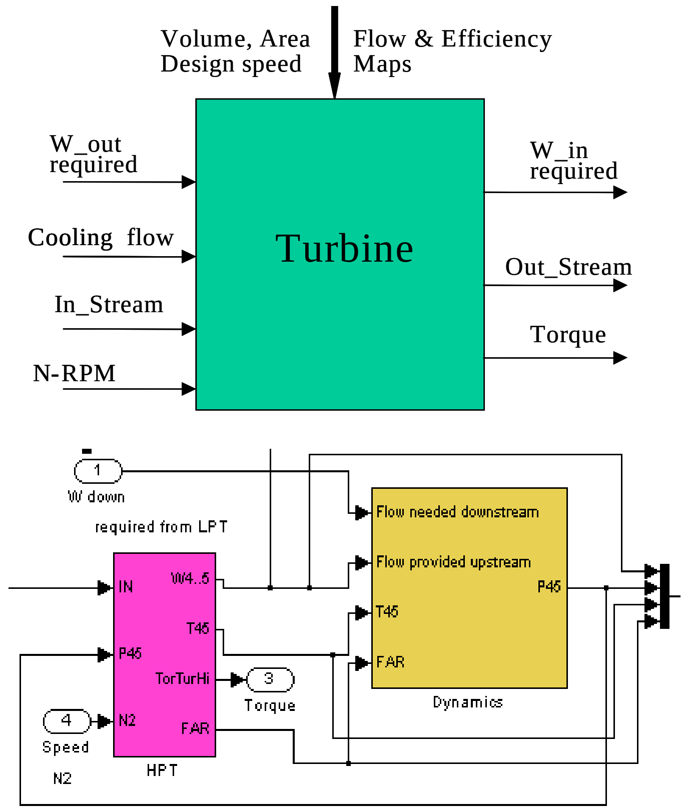

Figure 1. Example of the Turbine Module

III. METHODOLOGY

The major software modules created, along with the components they can instantiate are listed in Table 1 below:

	Parent Module	Instantiated Component Model
1	Compressor	Fan Hub, Fan Tip, Fan Overall, HPC, LPC
2	Turbine	HPT, LPT
3	Combustor	Combustor and Afterburner
4	Nozzle	Exhaust Nozzle
5	Inlet	Inlet conditions
6	Mixer	Mixer/ By Pass ratio resolver
7	Shaft	Fan shaft, Core shaft
8	Bleed/Cooling	Combustor cooling, HPT cooling, LPT cooling
9	Duct	Bypass duct, mixing duct
10	FADEC	Control Scheduled N1 through WF_demand

Table 1. Parent modules and instantiated components

The modules were developed based on fundamental laws of physics such as conservation of mass, momentum, and energy, consistent with classical industry modules, as documented in NPSS. The modules specifically adhere to rules on use of PHI for the derivation of ideal conditions.

Each component is modeled by instantiating its parent module through use of specific component maps, geometric and design data. Each component module has its static/steady-state and dynamic sub-modules. For a compressor or turbine the volume dynamics are based on the air in the volume after the module and before the next module. The dynamics for shaft are based on moment of inertia of the components attached to the shaft. The steady-state modules use the input conditions and static equations to obtain flow conditions from maps. Thus in order to use individual components to create an engine model, all hardware component information such as flow, pressure ratio and efficiency maps, flow volume and area of internal piping, are required. In addition gas tables are also required to calculate enthalpy and specific heat for pure air and fuel air mixture as a function of temperature, pressure and fuel-air ratio in different components.

The listed modules can be used to create a single spool or turbofan engine model if design data and maps relevant to the engine are available. These two steps should be followed:

1) Instantiate each module to create the relevant component – This step requires adding component specific information to the module. For example for a Low Pressure turbine, this information will include table names for the flow and efficiency maps, lumped volume, design speed and design point pressure ratio (design parameters are assigned structured names to minimize the effort of instantiating the module).
2) Link each component in a physical manner (upstream to downstream) – The components are linked upstream to downstream because they are created to simulate flow from inlet to exhaust for each component.

A simple example of how a single spool can be created using the components is shown in Figure 2. In this particular example a compressor, combustor, shaft, turbine and cooling modules are instantiated to simulate the core of an engine. This can be made into a single spool engine by adding an inlet and exhaust nozzle.

In this example, inlet conditions (In2) and fuel demand (Wf) determine the operating condition of the engine. For a fixed inlet, increases in Wf result in increases in rotor speed. Beyond this simplistic statement, there are a lot of details that affect how much and how quickly the speed responds. The structured model input data give the user adequate control over these details.

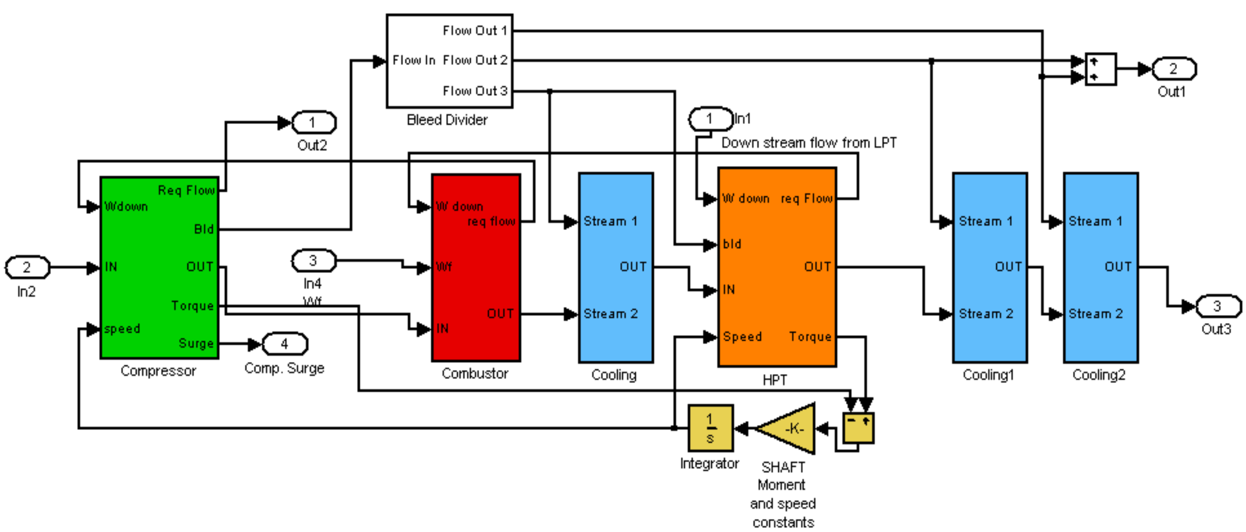

Figure 2. Simple Layout for Single Spool

	Inlet	FanT	FanH	HPC	Comb	Comb. Dome	Comb. Panels	HPT	LPT	BPDuct	Core	Mixer	After burner	Nozzle
NcDes		9690	9690	15307				6384	4362					
S_WcDes (Cd)		0.004	0.005	0		0.97	0.93	-0.057	-0.054					0.993
S_PrDes	0.000	0	0	0				0.000	0	0.000	-0.041	-0.001		
S_EffDes		-0.011	-0.011	-0.011	0.000			0.030	0.029			1.000		0.986
S_DHDes		0	0	0				0	0					
RlineGuess		4.7	4.7	5.2										
PrGuess		1.7	1.6	23	22			7.0	1.6	X	X			
VSVsched				0										
Diameter, in		38.5	X	14		3	0.5	X	X					29
Area_i, sq_in	1100	1100	1100	130		21.5	40	16.5	66			964		
Area_x, sq_in		900	180	31.5	30	37	37	77	180	800	163.4	964		664.4
Length, in	36	6	6	1.5	13	21		1.2	2.9	80	20	12		30
Volume_x,cu-in		70000	1728	800	800			728	3800			28000		
Loss_Coef	0.012				1.5					0.12				
Rey_ref	7E+06	1.6E+05	1.6E+05	5.1E+04	4.0E+05	1.5E+05	6.7E+05	9.4E+04	7.4E+04	9.0E+06	X	X		X
exp_Rey														
mass		X	X	6	14			8	19					
Tau_ref		7	7	1.4	1.6	2.2	1.7	1.8	2.2					

Table 2. Component Structured Data

IV. STRUCTURED DATA

The data structure emulates that in the MAPSS program and the NPSS program, with the naming convention being more like NPSS. It is logical enough that a user can determine the name of the parameter when modifying a value in a component's module. For example, in the core engine compressor, the design efficiency scalar is HPC.S_EffDes. If a copy of the same module is later instantiated as the LPC of a turbofan engine, then the parameter becomes LPC.S_EffDes, simply changing the HPC to LPC. This was intended to greatly simplify the process of constructing the model without some kind of full automation. Table 2 contains example input component level structured data. Table 3 contains some other structured data names.

Parameter	Value
Fuel.LHV	18400
HPShaft.NDes	14723
HPShaft.Inertia	1.25
HPShaft.AGB.GR	0.377
HPShaft.Nlimit	106%
LPShaft.NDes	8700
LPShaft.Inertia	3.85
LPShaft.Nlimit	110%
LPShaft.AGB.GR	1.0
T45TC.Tlimit	2086

Table 3. Additional Structured Data

Special Features of Engine Model

Many simplified models leave out features that are critical to matching detailed cycle deck output values. This generic model began with some simplifying approaches, like using specific heat (Cp) to calculate component work with the ideal equation method used in many models, but the complexity was increased for the following:

Thermodynamics: H and PHI tables with dissociation were adapted from available thermodynamics tables, including JANAF (Joint Army Navy Air Force) and in agreement with that used in NPSS. PHI is used to calculate ideal work for the components and used with enthalpy (H) to calculate efficiency, instead of the ideal equation method used in many models, including Gastineau [2] and Yadav, et al [5]. Dissociation is assigned at equilibrium and the ability to "freeze" the constituents was not implemented.

Reynolds Effects: Reynolds Numbers at the local conditions are compared with reference Reynolds Numbers to get the effects on flow, work and efficiency (or loss). Application of these effects allow the correct performance adjustments with altitude. All components have Reynolds number calculations and the effects are assignable. Heat transfer to metal components is also dependent on the Reynolds number.

V. Controls Model

The controller knows the engines state only by what the sensors feed back to it. Sensors may have error or lag, which can be ignored or compensated. Some functions that the controller should control (like thrust or surge margin) have no sensors, so the controller may control to a substitute parameter (like N1R instead of thrust) . Figure 1 shows the relationship of the sensor input to the controller. Sensor data is held in the controller's input buffer until the beginning of the next process cycle.

Sensor feedback parameters determine the error (how much the parametric should be caused to change). The parameter errors can be reduced in future time slots by changing actuator commands. The actuator command changes are determined in the "P-I Controls" (Proportional-Integral) module. The logic determines actuator commands for several control modes. Currently, only fuel ratios WF/P3 are manipulated to meet the PLA demand, but other residual capabilities are inherited from the MAPSS controller.

The output commands go to actuators that then effect changes to the engine inputs and settings, like fuel flow and variable stator vane (VSV) angle. Actuators have errors, time lags, hysteresis and physical limits. Errors in the actuator may not be fed back to the controller.

Simulation Inputs and Set Up

The engine simulation has four user inputs. Altitude, Mach number and dTamb are the ambient inputs, and power is set by the PLA. All inputs can be changed by varying the associated Simulink slider, while the model is running. The inputs are detailed below.

1) Altitude – This is an ambient input and its range is sea level to 70,000 feet. The altitude input goes into the Aircraft subsystem of the input module.
2) Mach number – This simulates the mach number of the aircraft and its affect on P2 and T2. The range for Mach number is 0 to 0.95. Modifications can be made for supersonic flight.
3) dTamb – The difference in ambient temperature from that of a standard day. It changes T2 at any altitude.
4) PLA – This is the control input. It goes to the Controller subsystem and calculates the fuel ratios to the model. N1_demand is compared to the feedback N1 and this error is used to adjust the fuel demand.

While running on a stand-alone PC, these sliders are suitable to rapid changes in a single input value. On the real time bench, the aircraft climb path, fluctuations in inlet temperature and PLA rate changes can be programmed to give realistic desired results.

In the ICF, the models were separated into two units, one for the engine simulating continuous time operation, and the other running the Controller, simulating discrete time operation.

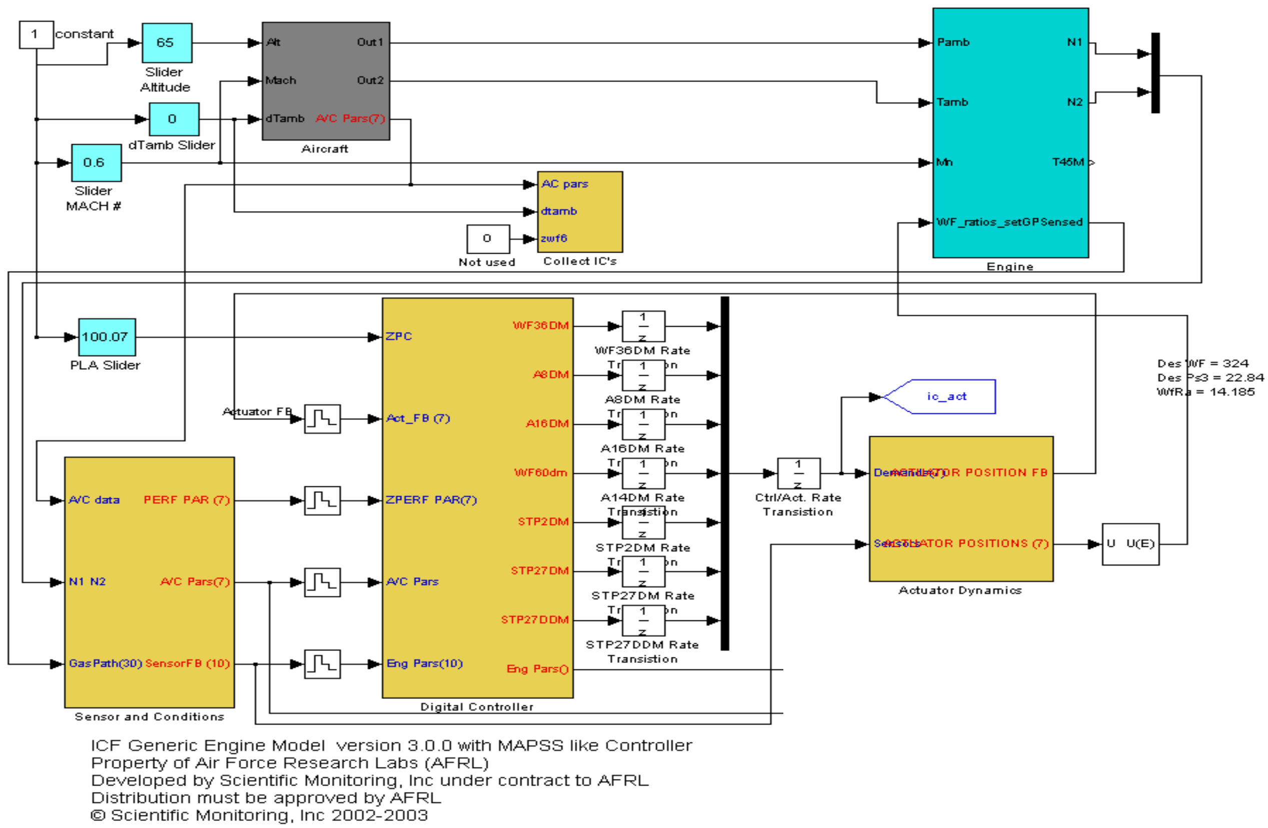

Figure 3. Top level View of Simulated Elements, such as Engine and Controller

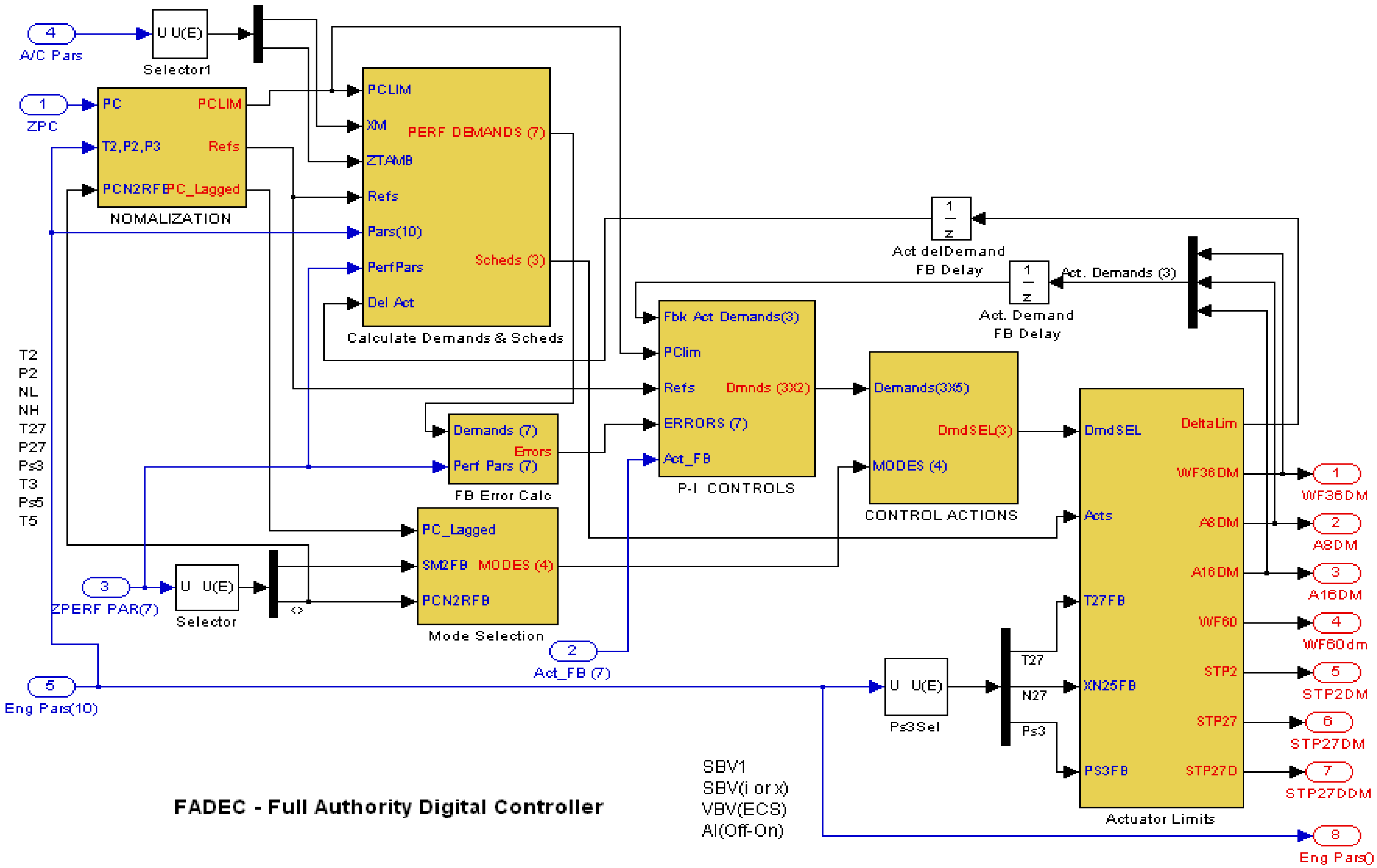

Figure 4. Layout of the Control Functions (derived from MAPSS)

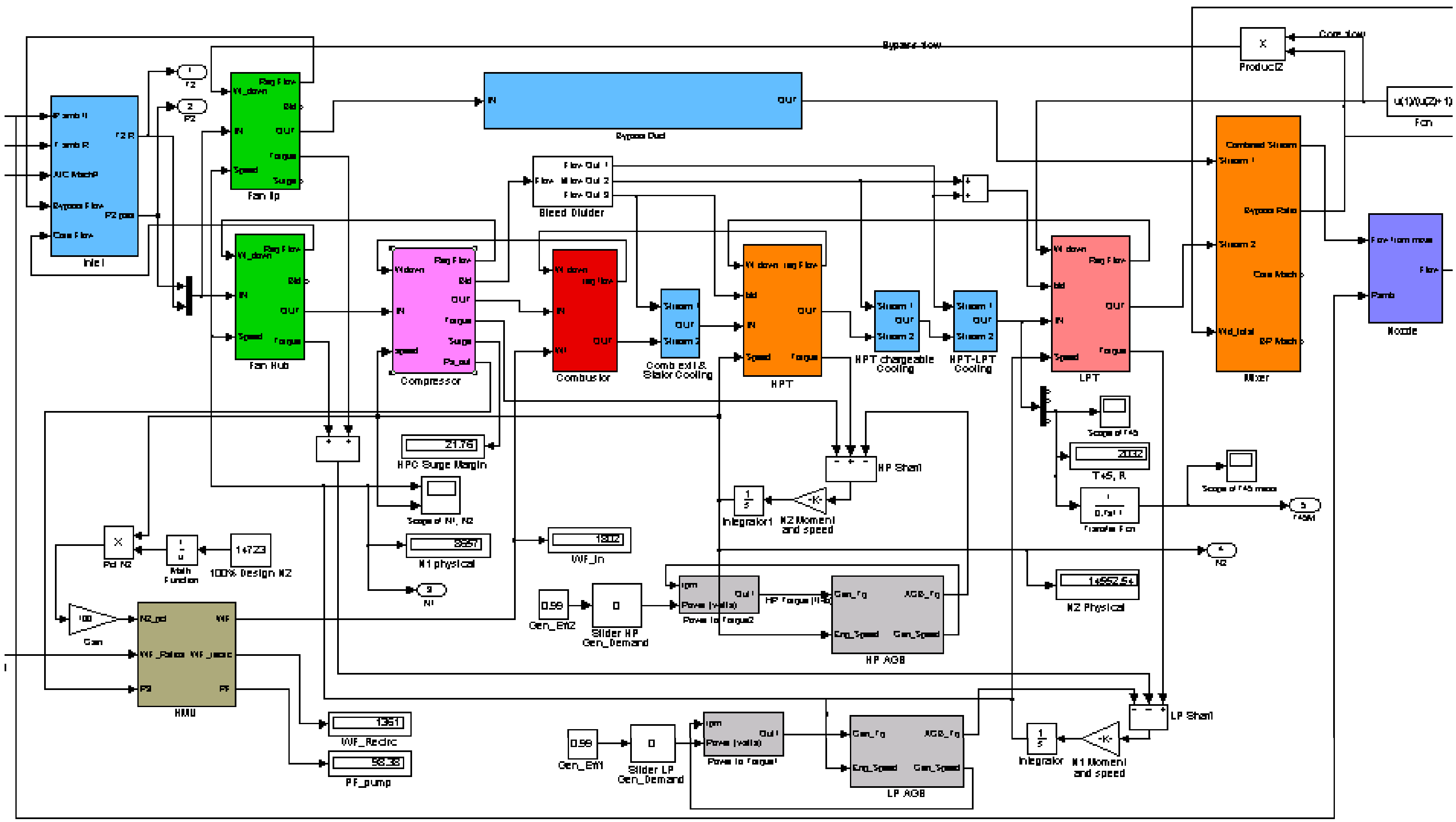

Figure 5. Turbofan Engine model built from instantiated modules

VI. Physical Setup

In the ICF, the models were separated into two rack units as shown in Figure 6, one for the engine simulating continuous time operation, and the other running the Controller, simulating discrete time operation. The models communicated only through physical connectors carrying actuator and sensor signals.

Figure 6. ICF HIL Laboratory Setup

VII. Testing and Demonstration

Since there was not a real engine with which to compare model results, A test description was proposed to demonstrate "reasonableness". The model was demonstrated with PLA movements at various altitudes. There is no definitive baseline with which to compare the generic model results.

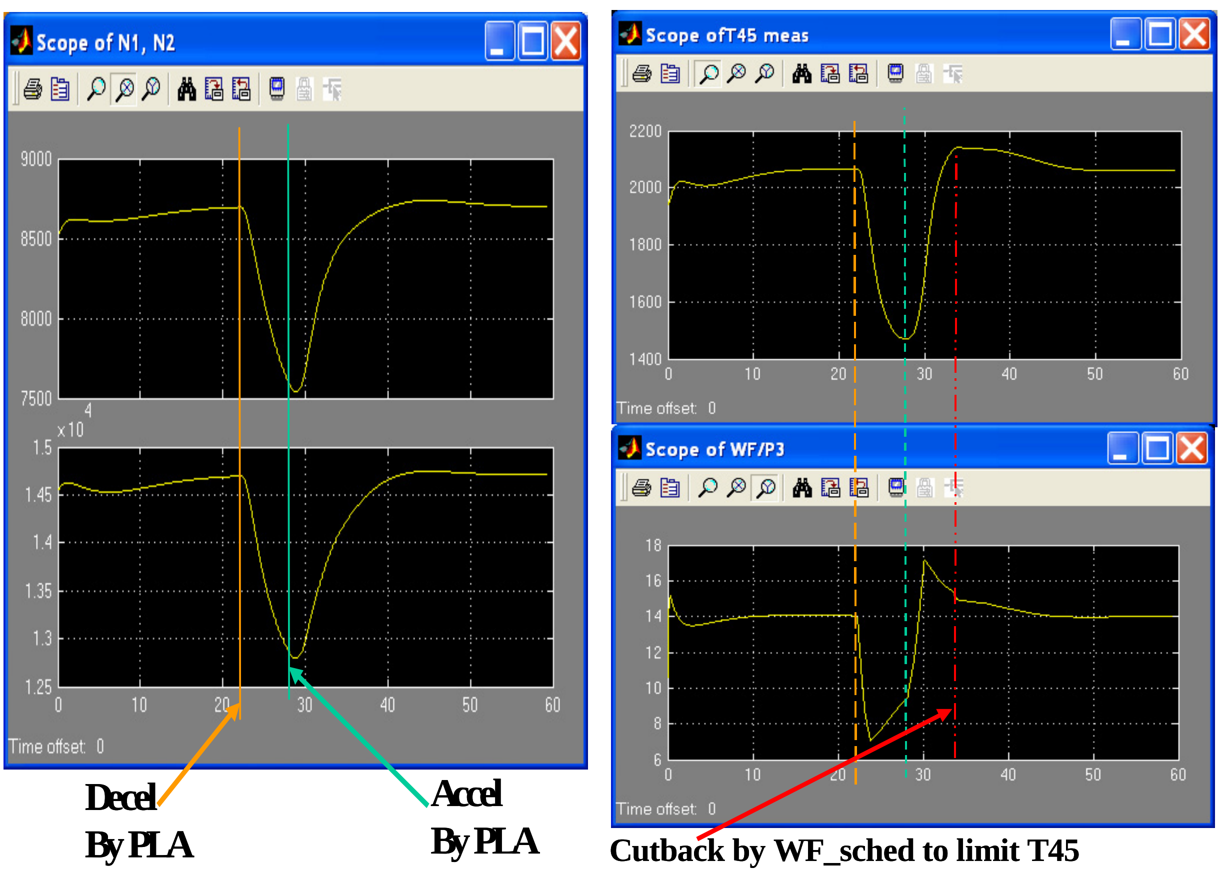

Figure 7. Trace of generic model responses with PLA Movements

Figure 7 presents the behavior of the engine model as represented by a few parameters, N1, N2, EGT and WF/P3 ratios. In Figure 7 the EGT limit was set to assure that the limit would be hit upon re-acceleration, to see how the model behaved trying to maintain that limit. This demonstration was run on the single computer rather than on the separate engine and control units.

A significant part of validation for the generic model is the use and confirmation of standards in the thermodynamics and the calculations. During this model development, each module's computations were compared to those in the NPSS model of the same generic cycle. Further validation may be attempted by comparison to engine or other simulation data. A proposed validation plan may include the following steps:

1. Choose an engine cycle for which component maps, physics, control laws; steady-state and transient data are readily available.
2. Modify the generic ICF model to incorporate that specific input data.
3. Verify the design point cycle data and the component Reynolds effects.
4. Run a series of steady-state and PLA transients around the flight envelope for which a comparison to the target cycle is available.
5. Compare critical engine values with those of the model.

Such a validation plan will require significant effort and the use of proprietary data. Once validated, this model can be used to see the effects of changes, such as control law changes, health monitoring algorithms and life extending logic.

VIII. Further Applications

The following are some recommended applications of the ICF model:

- Investigation of control law changes for a fielded engine.
- Investigation of new improved FADEC algorithms including Model-Based Control.
- Replacement (or even addition) of sensor and actuator characteristic models and observation of changes in behavior.
- Integration of engine models with models of other aircraft subsystems that interact with it.
- Study of changes in engine health management algorithms, looking for improved fault detection and longer engine life.

These recommended applications will result in better understanding of control laws for both legacy and new engines, and better understanding of diagnostics, prognostics and control integration issues. Through modeling and simulation, we can achieve improved operation of turbine engines by improving software and hardware (including sensors, actuators, and related systems). The benefits of using simulation to carry out these tasks are reduced cost, time and risk compared with classical techniques using demonstrator engines. Overall, simulation will provide better understanding of engine/vehicle system integration issues prior to hardware fabrication or technology transition, for both hardware and software, and will thus have a major impact in reducing program risk.

IX. Concluding Comments

The ICF generic engine model with controller is an important component of the hardware-in-the-loop goal of the ICF. Once the engine simulation is validated, many tests that have been run on engines can be relegated to the ICF in a much shorter time and at a significantly reduced cost.

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XI. ACKNOWLEDGEMENTS

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And at AFRL in Dayton, Ohio, Mr. Daniel Tasch for his encouragement for the modeling efforts on the ICF project and Dr. Zane Gastineau who originated this model development work at AFRL before Scientific Monitoring, Inc. started working on it in June 2002.

Biographical Notes

George Mink is an Engineering Vice President at Scientific Monitoring, Inc. He has a BSME from Carnegie Mellon University and a MSME from Rensselaer Polytechnic Institute. He has had a long career in performance of aircraft engines at Pratt & Whitney Aircraft and Honeywell International, with focus on fault detection and root cause analysis. He trained in and practices Six Sigma. He is currently concentrating on issues of automated detection, isolation, prognostics and corrective actions.

Alireza Behbahani, Ph.D. is currently a senior aerospace engineer in the Propulsion Directorate in the Turbine Engine Division (PRTS) at the United States Air Force Research Laboratory, Wright Patterson Air Force Base, Ohio, where he is the Group lead for Controls and Engine Health Management . Dr. Behbahani started as a senior program Manager at the PRTA. He has a BSEE from Utah State, and MS and Ph.D. from the Ohio State University. He has an extensive modeling, simulation, controls-related research, development, integration, and testing experience. Previously he was the Project Leader / Lead Engineer- CF6 Control Systems, Commercial Control Systems - Controls, Center of Excellence at the General Electric Aircraft Engines, Cincinnati, Ohio. Among many publications, he also co-authored FADEC-Aircraft interface Document (FICD) for C-5 re-engine program and designed and developed Power Management and Thrust Reverser for control system of aircraft engine. He has also served as an engineering consultant, Senior Research Associate, Senior Engineer at various positions and a faculty member at the University of Cincinnati, Department of Mechanical, Industrial, and Nuclear Engineering.